Rotational Excitation of CO in the Diffuse ISM: Effects of Line Emission from Dense Molecular Clouds

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ABSTRACT

We discuss a somewhat neglected interstellar excitation mechanism by means of which CO can be rotationally excited in diffuse gas ($n_{tot} \leq 300$ cm^{-3}). Where strong density contrasts exist, say where diffuse gas abuts a dense interstellar cloud, we show that molecular excitation in the diffuse gas may be dominated by spectral line photons emitted by the denser material. Failure to account for such excitation may result in a severe over-estimation of space density in the diffuse gas. We develop a simple 2-state model and apply it to the case of $J = 1 \rightarrow 0$ CO. Line-of-sight analyses of CO excitation can be (and have been) misinterpreted due to neglect of this contribution to radiative excitation. Similar situations can arise whenever there is a small continuum opacity and a large density contrast within, or around an interstellar cloud. It is a situation where the often-used Large Velocity Gradient (LVG) approximation simply does not apply.

Subject headings: ISM: clouds, kinematics and dynamics—ultraviolet: ISM—

1. Introduction: the rotational excitation of CO

The ultraviolet systems of CO (A-X, B-X and C-X) contain many bands, each separated into lines from individual rotational levels. Data from any one of the bands can be used to evaluate the rotational excitation, and the fact that the bands have different intrinsic line strengths ensures that optical depth effects can be minimized along virtually any line-of-sight. For many years CO excitation has been used to make inferences about the gas density and temperature in the diffuse ISM (c.f., Smith, Krishna Swamy & Stecher 1978; Lambert et al., 1994). The analyses typically assume that excitation is due to the $\approx$3 K Cosmic Background Radiation (CBR) and to collisions with hydrogen in atomic and/or molecular form, balanced by radiative de-excitation. Some lines-of-sight exhibit very modest excitation temperatures (3 - 6 K), yet the derived gas densities are seldom much smaller than 100 cm^{-3} due to the demands imposed by spontaneous emission. During the course of evaluating recent GHRS observations toward lines of sight near the molecular cloud B5, we re-examined the usual approach and realized that spectral line emission from dense molecular clouds may provide an important, and even dominant source of rotational excitation (Wannier et al. 1997a; Wannier et al. 1997b). Such a finding would invalidate gas densities derived under the assumption that only collisions can elevate the excitation temperature above the temperature of the CBR. The B5 sightlines are unexceptional in terms of their physical properties, so that the same considerations are likely to apply to other sightlines, such as the more familiar one toward ζ Oph.

What degree of excitation can be provided by millimeter-wave emission, and what is the relative spectral emission vs continuum emission from dense clouds? For the $J = 1 \rightarrow 0$ line of CO at $\lambda = 2.7$mm, the average dust opacity in the B5 molecular cloud is $\approx 10^{-2}$, yielding a continuum brightness of ≤ 0.1 K (Cernicharo & Bachiller 1984; Savage & Mathis 1979; Whittet 1992). Therefore, the two largest radiative inputs in diffuse clouds are likely to be from (1) the cosmic background radiation (CBR) (2.73 K), and (2) line radiation emanating from nearby dense gas: in our example the B5 molecular cloud (figure 1). We assume, based on observations of the B5 region that the absorbing gas is located adjacent to the B5 cloud, an assumption supported by the agreement of V_{lsr}, and from our observations of HI 21 cm emission, which suggest that the CO forms part of an outflow from the B5 cloud (and92). For a dense cloud of uniform brightness temperature, the line radiation is then easy to estimate. Since CO spectral lines are normally reported as being that intensity in excess of the CBR, the excitation temperature of a CO molecule, in the absence of collisions, will exceed the CBR temperature by an amount roughly proportional to f times T_R where f is the fraction of the total solid angle subtended by the dense cloud, as viewed by a molecule in the absorbing gas, and T_R is the brightness temperature of the CO $J = 1 \rightarrow 0$ emission line. If T_R = 10K (which is more or less true for B5), and $f = 0.1$, then we get excitation rates sufficient to account for an excitation of about 4 K. Because the observed rotational temperature is not significantly larger than this, collisions may well not be significant, and therefore the CO observations may only allow one to place upper limits on the space density of the absorbing material.

Because the radiative excitation results from spectral line absorption of spectral line radiation, the relative velocities of the diffuse and the dense gas must be considered: specifically, the radial velocity of one as viewed by the other. Some uncertainty must inevitably result from our lack of knowledge about motions in the plane of the sky. Spectral line coupling will occur whenever the velocities of the absorbing and emitting material are the same, as projected along the line-of-sight connecting them. We can check that both parcels of gas have the same radial velocity along the line-of-sight to the Earth, but strictly speaking that is neither necessary nor sufficient to prove that radiative coupling actually exists. For our example, we assume that coupling exists if and only if we see agreement in V_{lsr} between the emitting and the absorbing gas. This assumption enables us to estimate the radiative coupling based on actual maps of CO brightness temperature, although the coupling may be either over- or underestimated.

2. CO Excitation for the 2-level case

The calculations are complicated by two facts: (1) molecular clouds are not uniformly bright, and (2) brightness temperatures are generally reported as if the Rayleigh-Jeans limit applies, which is not the case we consider. Nonetheless, it is straightforward to evaluate the excitation temperature for a molecule, irradiated by the CBR and a nearby dense cloud. We assume that the absorbing CO is embedded in a gas of temperature T_k and density n, consisting primarily of H_2. The excitation temperature for a 2-level system ($J = 0$ and $J = 1$ CO in our case) is then:

$$T_{ex} = \frac{T_k}{1 - \frac{T_k}{T_*} ln \left\{ \frac{\frac{C_{10}}{A_{10}} + e^{T_*/T_k} \left[\frac{T_R^e}{T_*} + \frac{1}{e^{T_*/2.73}-1} \right]}{1 + \frac{C_{10}}{A_{10}} + \left[\frac{T_R^e}{T_*} + \frac{1}{e^{T_*/2.73}-1} \right]} \right\}} \qquad (1a)$$

where $T_* = h\nu/k = 5.53K$ for the $J = 1 \rightarrow 0$ CO line, T_R^e is the total effective $J = 1 \rightarrow 0$ CO line intensity as viewed by the absorbing gas, and C_{10} and A_{10} are the usual de-excitation rates due to collisions and spontaneous radiation. T_R^e is the total radiation intensity as viewed by the absorbing gas, so:

$$T_R^e = \frac{1}{4\pi} \times \int_0^{2\pi} \int_0^{\pi} T_R(\phi, \theta) sin(\phi) d\phi d\theta \qquad (2a)$$

where T_R is the conventional measure of millimeter-wave spectral line intensity, and is most accurately understood as the intensity in excess of the CBR, reported in temperature units (c.f., Kutner & Ulich 1981). For an emitting cloud of uniform brightness temperature, we can write

$$T_R^e = f \times T_R \qquad (3a)$$

where f is the fraction of 4π steradians subtended by the cloud as viewed by the absorbing gas. Results for this simple case are shown in the several panels of figure 2, which present T_{ex} as a function of density for a cloud with a CO brightness temperature, T_R, of 10 K, and for several combinations of f and T_k. It is evident that for values of f as small as 0.1, the molecular excitation is raised to a level comparable to that produced collisionally by gas densities of several hundred. Since a filling factor of 0.1 is not uncommon for typical molecular lines-of-sight, we infer that CO excitation cannot be used reliably to infer space densities of much less than 1000 cm^{-3}. Such inferences have, however, been made. In the well-studied line-of-sight toward ζOph, for example, Smith, Krishna Swamy & Stecher 1978 have used CO excitation to infer that the total mean density of hydrogen lies in the range from 48 to 360 cm^{-3}, assuming that excitation is due to collisions with H_2 molecules and to the CBR.

In most applications, equation 2 cannot be evaluated directly because the line-of-sight CO distribution is simply not known. Said another way, we may have insufficient information to evaluate the effective solid angle, f. Therefore, some additional assumption is needed, even if a complete CO emission-line map is available. We have therefore assumed that the emitting gas in any cloud or cloud fragment is circularly symmetric as viewed by the absorbing gas (see figure1). This can lead to either an overestimate or underestimate of T_R^e. It is accurate for the case where the emitting gas is in a spherical cloud, and the absorbing material, for example, might lie in the extended periphery of the cloud at a tangent point. Then the double integral in equation 2 becomes a single integral along ϕ, the angle measured from the axis of symmetry, lying in the plane of the sky. For a cloud of uniform surface brightness at the $J = 1 \rightarrow 0$ line frequency, eqn. 2 then becomes

$$T_R^e = T_R \times (1 - cos(\phi_1))/2 \tag{4a}$$

where ϕ_1 is half the opening angle of the dense cloud as viewed by the absorbing material.

In their analysis of three lines-of-sight near B5, Wannier et al. 1997b obtained values of f in the range 0.05 to 0.25. The locations and brightnesses of the emitting cloud fragments were taken from Langer et al. 1989.

Equation 1 is valid only for a 2-level system, but the analysis is easy to generalize to multi-level systems, so long as the intensity of the exciting (millimeterwave) emission is known for each rotational transition. For the three B5 lines-of-sight of Wannier et al. 1997b, strong UV absorption was detected from J=0 and J=1, and significantly weaker absorption (smaller column densities) was found from J=2. Higher levels were not sufficiently populated to yield detections. The $J = 2 \rightarrow 1$ emission-line intensities could be estimated from the observations of Young et al., 1982. However, we found that the combination of the weaker $J = 2 \rightarrow 1$ emission and the small, observed, level J=2 population made the exercise of including the J=2 rotational level unenlightening and unrewarding.

3. Conclusions

We have re-examined the rotational populations of CO in diffuse clouds, and have concluded that they are often consistent with radiative excitation by millimeter-wave spectral-line emission from nearby dense clouds. This result invalidates prior analyses which have instead assumed that the excitation results from collisional excitation. We find that inferred space densities, n_{tot} of $\leq$1000 cm^{-3} should be re-evaluated, and that inferred densities of $\leq$100 cm^{-3} are almost certainly wrong (or at least not inferrable based on the CO excitation). Instead, the CO rotational lines provide upper limits to the space density, and derived pressures may be less than previously thought.

Wherever strong density contrasts exist, molecular excitation in the less-dense gas may be dominated by spectral line photons emitted by the denser material. In such circumstances it is simply not valid to use the "LVG" approximation to evaluate molecular excitation. This situation might also apply to molecular transitions near dense cores or dense protostars within molecular clouds.

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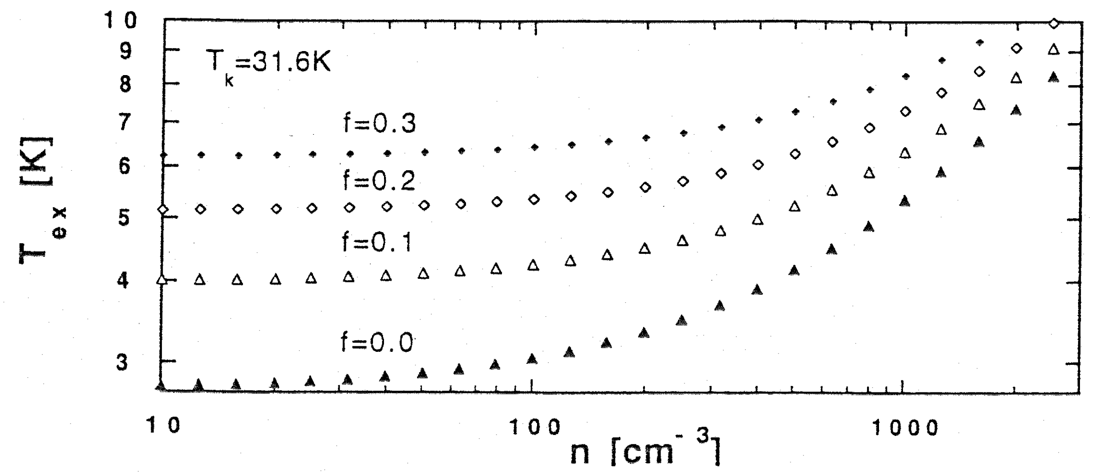
Fig. 1.— The geometry of of the gas is indicated, showing the absorbing molecule lying alongside a dense molecular cloud. The angle ϕ corresponds to that in equations 2 and 4.

Fig. 2.— T_{ex} is shown as a function of density for a cloud illuminated by the CBR and by millimeter-wave emission from dense molecular gas (CO brightness temperature, $T_R = 31.6$ K). The first panel (a) is for a gas kinetic temperature in the diffuse gas of 10 K, panel (b) is for $T_K = 100$ K and panel (c) is for $T_K = 316$ K. The parameter f is the solid angle (fraction of 4 π) subtended by the dense molecular cloud as viewed by the diffuse gas, so $f = 0.0$ presents the analysis neglecting the effects of spectral line radiation from the dense cloud. Therefore, for $T_K = 100$ K and $F = 0.1$, the excitation provided by the millimeter-wave spectral line radiation is equal to that produced by a gas density of 330 cm^{-3}. The effect of the spectral line emission is more prominent for larger values of f and/or smaller values of T_K.



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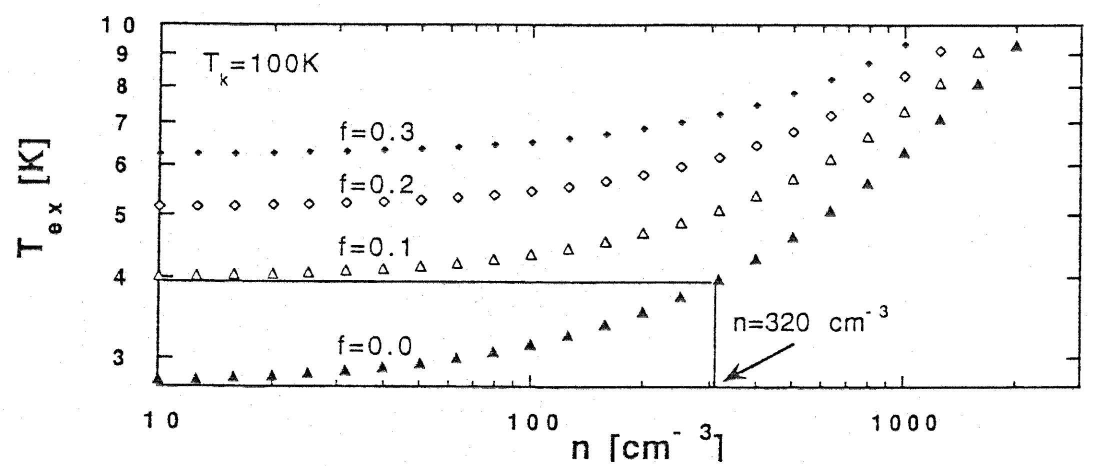
f=0.1
f=0.0
T_{ex} [K]
n [cm^{-3}]



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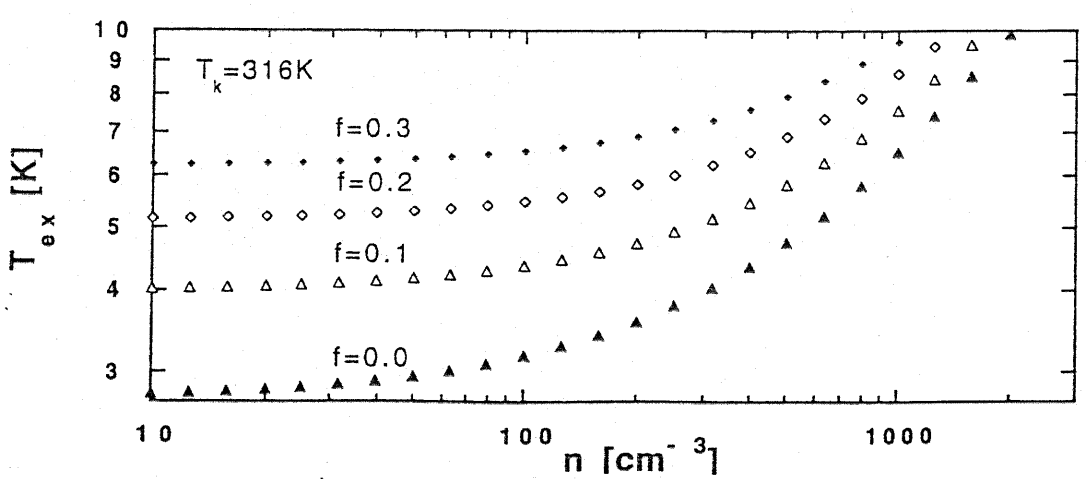
T_{ex} [K]
n [cm^{-3}]



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T_{ex} [K]
n [cm^{-3}]